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# High Resolution Measurements of Supersonic Shear Flow Mixing and Combustion

Werner J.A. Dahm and James F. Driscoll

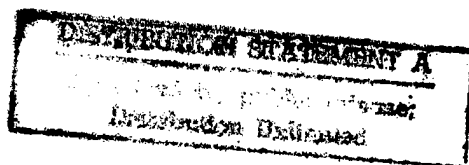
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Department of Aerospace Engineering  
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# HIGH RESOLUTION MEASUREMENTS OF SUPERSONIC SHEAR FLOW MIXING AND COMBUSTION

AFOSR Grant No. F49620-98-1-0003

Werner J.A. Dahm and James F. Driscoll

*Laboratory for Turbulence & Combustion (LTC)*  
*Department of Aerospace Engineering*  
*The University of Michigan*  
*Ann Arbor, MI 48109-2140*

## Summary/Overview

Achieving supersonic mixing and combustion while maintaining acceptable flame stability characteristics and emissions of trace chemical species are key to the development of improved airbreathing propulsion systems. The present investigation contributes to this objective by making high-resolution imaging measurements of the physical structure of supersonic mixing and combustion in a turbulent shear flow. The work consists of two major parts.

The first part is an experimental and theoretical investigation of the outer-scale properties of mixing and combustion in a supersonic shear flow facility. Emphasis is on measuring changes in the large-scale structure and growth rate of a two-dimensional supersonic turbulent shear flow due to compressibility effects, and comparing with results obtained in supersonic mixing layers elsewhere in the AFOSR program. Comparisons with results from mixing layers allow identification of the effects of compressibility that are generic to all supersonic turbulent shear flows. This work also builds on recent advances in understanding density effects due to heat release on the growth rates and other outer-scale properties of turbulent shear flows. Density effects due to compressibility are being analyzed similarly to develop fundamental understanding and predictive modeling capabilities for supersonic turbulent shear flows.

The second major part of this work is investigating the fully-resolved four-dimensional spatio-temporal structure of the fine scales of molecular mixing in subsonic and supersonic turbulent shear flows. A recently-developed measurement system will permit the first-ever simultaneous study of the combined four-dimensional spatial and temporal structure of the conserved scalar field  $\zeta(\mathbf{x},t)$ , the molecular mixing rate field  $\nabla\zeta\cdot\nabla\zeta(\mathbf{x},t)$ , and the underlying vorticity and strain rate fields  $\omega_i(\mathbf{x},t)$  and  $\epsilon_{ij}(\mathbf{x},t)$  in a gaseous turbulent shear flow. These measurements will permit essential new insights to be gained into the fundamental issues that dominate the coupling between turbulent flow, molecular mixing, and nonequilibrium reaction chemistry in turbulent combustion systems.

## Technical Discussion

During the past year we have obtained extensive experimental results for the outer-scale properties and large-scale structure of supersonic turbulent jets operating in the wake mode. Typical results are shown in Figs. 1 and 2. There are indications that the large-scale structure of the flow, which is clearly evident in the further downstream parts of the flow, where the local Mach number has become subsonic, may be suppressed in the upstream portion of the flow. This is being further investigated. However, the local flow width  $\delta(x)$  and growth rate  $d\delta/dx$  in Figs. 2 and 3 show results consistent with the  $(x/\delta)^{1/2}$  scaling that is characteristic of the corresponding subsonic flow, even in the upstream parts of the flow. This can be clearly seen in the log-log plots in Fig. 3, where it can be further observed that this conclusion appears to be independent of the choice of flow width definitions.

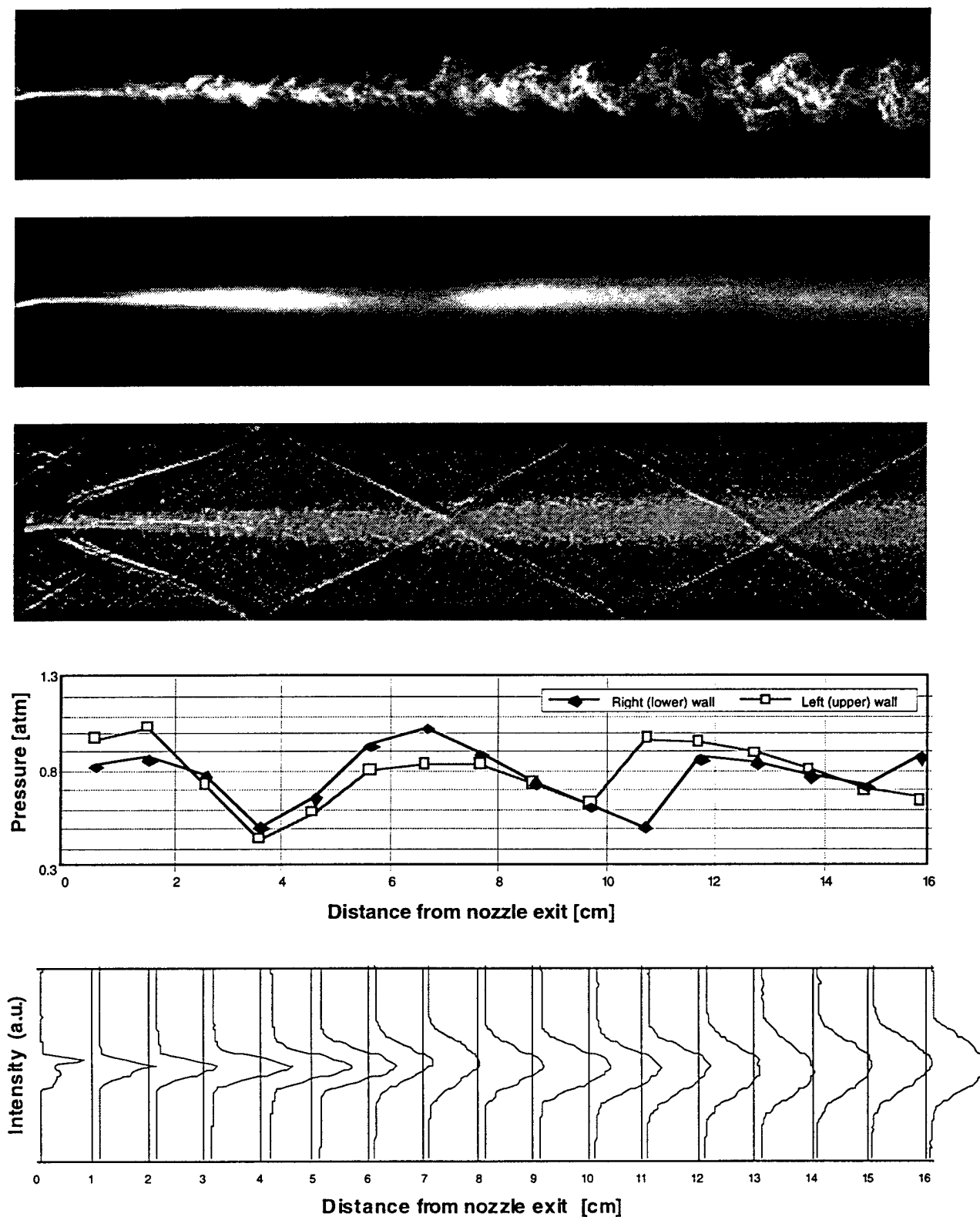


Fig. 1. Typical experimental results for outer-scale properties obtained in the two-dimensional supersonic turbulent shear flow, showing instantaneous mixing regions and large-scale structure as visualized by alcohol fog technique (*top*), ensemble average (*second*), with supersonic wave structure superimposed (*third*), wall static pressure measurements (*fourth*), and local flow width  $d(x)$  as indicated from second panel. See also Fig. 2. Growth rates obtained from bottom panel are shown in Fig. 3.

Several supersonic hydrogen-air flames were imaged in our Supersonic Mixing and Combustion Facility. Acetone PLIF was used to visualize the fuel concentrations in the jet-like flames, and OH PLIF was used to visualize the reaction zones. The supersonic flames that were studied were partially lifted, having a flame base that is stabilized in a recirculation zone behind the bluff-body fuel injector. It was found that the structure of the supersonic flames is closer to that of a partially premixed flame, and is very different from the structure of a conventional attached subsonic jet flame.

The partial premixing of hydrogen and air is enhanced by the extremely strong recirculation zone downstream of the fuel injector, which is driven by the Mach 2.5 airstream. The OH reaction zone structure has the appearance of a tangled web of thin reaction layers for subsonic coflow air; as the coflow air becomes supersonic the layers become thicker and merge, and the instantaneous OH concentrations become spatially diffuse. The increased homogeneity of the OH reaction zone at supersonic conditions is attributed to the intense premixing of fuel and air prior to combustion. Our experimental observations provide strong evidence that the flame is partially premixed, which emphasizes the need to develop new models, especially those that can represent a complex set of reaction layers, some of which are diffusion layers and some partially premixed flames.

We have also initiated an ongoing interaction with researchers at the Air Force's WPAFB in Dayton, OH (T. Jackson, J. Donbar). The first phase of this interaction has been completed; Michigan Ph.D. candidates operated advanced PIV / OH / CH diagnostics at WPAFB to answer fundamental research questions relating to turbulent mixing and reaction. For the first time, the CH and OH reaction zone structure and the hydrodynamic strain rate were measured in an intensely turbulent nonpremixed flame. A regime of combustion was investigated in which the intense turbulence and long residence times provided extremely large degrees of flame wrinkledness and large values of flame surface density. Some partial premixing was observed in certain cases. The relevant nondimensional parameters that characterize this regime of combustion are being deduced from the data.

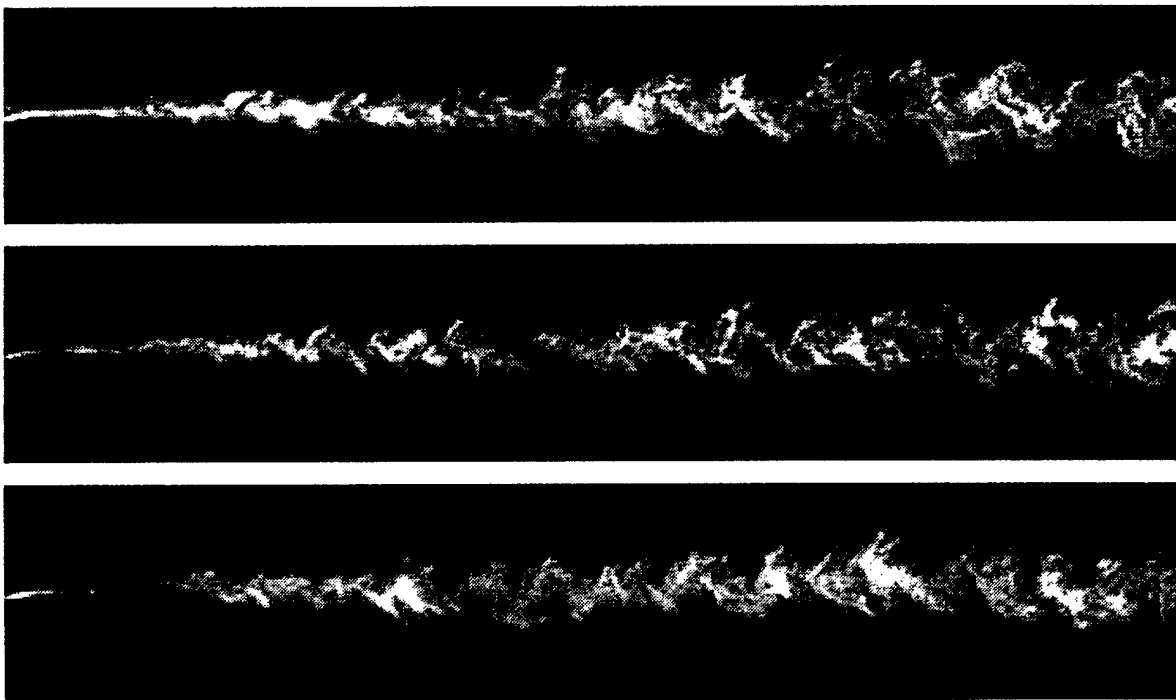


Fig. 2. Typical large-scale structure in the two-dimensional supersonic turbulent shear flow shown in three different realizations, visualized by alcohol fog technique. Note the large-scale structure is clearly evident in the farther downstream regions of the flow, where the local Mach number is subsonic.

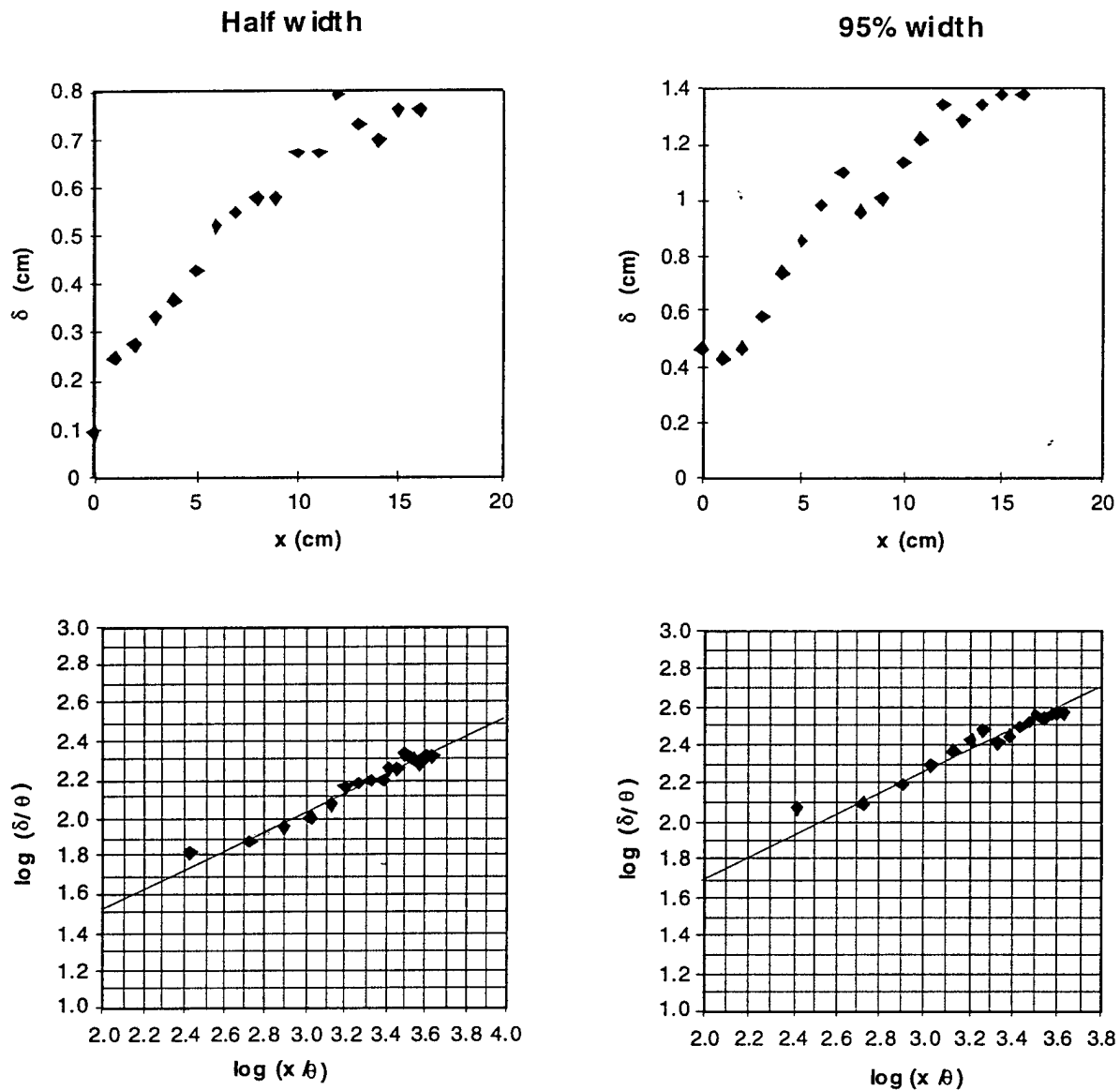


Fig. 3. Measured variation in local outer-scale flow width  $\delta(x)$  defined by half-width (*left*) and 95% width (*right*) with downstream distance  $x/\theta$  in the two-dimensional supersonic shear flow, shown in linear form (*top*) and logarithmic form (*bottom*). Note straight line gives  $(x/\theta)^{1/2}$  power law scaling.

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Buch, K.A. and Dahm, W.J.A. (1998) Experimental study of the fine-scale structure of conserved scalar mixing in turbulent flows. Part II.  $Sc \approx 1$ ; *J. Fluid Mech.* **364**, 1-29.

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**Principal Investigator Annual Data Collection (PIADC) Survey Form**

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Author(s): Frederiksen, R.D., Dahm, W.J.A. & Dowling, D.R.  
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Effects of Reynolds and Schmidt numbers

Author(s): Frederiksen, R.D., Dahm, W.J.A. & Dowling, D.R.

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Name of Journal, Book, etc: Journal of Fluid Mechanics

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Name of Journal, Book, etc: Proceedings of the 13th U.S. National Congress of Applied Mechanics

Title of Article: Global scalar field measurements and whole-field scalar imaging velocimetry in

turbulent flows

Author(s): Dahm, W.J.A. & Tacina, K.M.

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#### TECHNOLOGY TRANSITIONS

Result: d+ method for heat release effects on mixing

Customer: Energy Systems Associates (ESA)

Contact: Dr. Ben Breen, ESA (Pittsburgh, PA) (412) 429-3259

Application: Development of FLGR system at Duke Power Company's Riverbend Unit 7

Result: d+ method for heat release effects on mixing

Customer: Fuel Tech Inc.

Contact: Dr. Roy Johnson, Fuel Tech Inc. (Naperville, IL) (630) 983-3242

Application: Development of amine-enhanced FLGR system at PSE&G Mercer Unit 22

Result: d+ method for heat release effects on mixing

Customer: Praxair, Inc.

Contact: Dr. Sho Kobayashi, Praxair, Inc. (Tarrytown, NY) (914) 345-6470

Application: Development of DOC system Auburn steel reheat furnace